PROJECT EXODUS

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"In 1492, Columbus knew less about the far Atlantic than we do about the heavens, yet he chose not to sail with a flotilla of less than three ships ... so it is with interplanetary exploration: it must be done on the grand scale."

—Wernher Von Braun
Das Marsprojekt, 1952

INTRODUCTION

In 1952, Von Braun envisioned the first mission to Mars. He compiled a document entitled Das Marsprojekt that called for passenger and cargo ships as well as a landing craft. His idea was that the first mission would require many ships to reach the Red Planet.

Project Exodus is an in-depth study intended to identify and address the basic problems of such a mission. The most important problems concern propulsion, life support, structure, trajectory, and finance. Exodus, which means "mass migration" or "mass departure," will employ a passenger ship, cargo ship, and landing craft for the journey to Mars.

Project Exodus is scheduled for the year 2025. Construction of the vehicles will be performed at the Space Station. First, the cargo ship will be launched and then the passenger ship, known as the waverider, will be launched depending on the arrival of the cargo ship. The waverider, carrying 10 astronauts, will use the Venus atmosphere to perform an aerogravity assist for deflection angle and delta velocity savings for the trip to Mars. It will dock in low Mars orbit (LMO) with the cargo ship and the astronauts will descend to the martian surface using the landing craft, the Nuclear Rocket Using Indigenous Martian Fuel (NIMF shuttle). After three to five months on the surface of Mars the astronauts will again use the waverider to return to Earth and dock with the Space Station.

The cargo ship will transport the unassembled martian base, NIMF shuttle, surface life support, and return fuel and engine to LMO. The cargo ship is a very long truss to which the payload it attached. It is propelled in a spiral trajectory to Mars using a Nuclear Electric Propulsion (NEP) system.

The NIMF shuttle is used to transport the astronauts to the martian surface as well as around the planet. It is powered by a solid core nuclear engine that can use CO_2 as a propellant. The NIMF shuttle has a range of 650 miles, and will be used to bring the astronauts back to LMO with the waverider.

While on the surface the astronauts will construct a dome base that will be mostly underground to help shield against solar radiation. They will explore the planet, perform experiments, and attempt to extract useful substances, such as water, from the planet. The base will be the start for possible colonization.

This report presents the three major components of the design mission separately. Within each component the design characteristics of structures, trajectory, and propulsion are addressed. The design characteristics of life support are mentioned only in those sections requiring it.

WAVERIDER

The waverider is the hypersonic, manned vehicle designed to transport astronauts to Mars. It will use an aeroassist maneuver at Venus and then return them to Earth via a sprint mission.

The design process for the waverider begins by placing a generic shape such as a cone or wedge in a flow field to create a shock wave. The waverider leading edge is then created so that it is everywhere attached to the shock. Subsequently, the lower surface is designed along the streamlines present in the flow field. Finally, the upper surface is constructed along the freestream streamlines so that the pressure acting along the upper surface is simply the freestream pressure. Since each leading edge design corresponds to a unique waverider, an infinite number of waveriders are possible for each shock. However, software written at the University of Maryland can generate specific, optimized waveriders for a particular condition. Generally, these conditions are maximum lift-to-drag ratio, minimum coefficient of drag, and volumetric efficiency.

The particular shape chosen was optimized for a maximum L/D while also considering volumetric efficiency. The waverider has a L/D of 8.47, a length of 60 m, a maximum height of 6.01 m and maximum width of 16.43 m (Fig. 1).

The waverider will approach Venus with a velocity (relative to Venus) of 14 km/sec. This corresponds to a local Mach number of 71 (based on freestream temperature). It will experience intense aerodynamic heating effects during its passage through the Cytherean atmosphere. Designing an integrated structure and thermal protection system capable of withstanding the severe heating conditions represents a major technical hurdle.

Three-dimensional Advanced Carbon-Carbon (ACC) was chosen as the waverider structural material. ACC outperforms all other materials above 1250 K. It has a high emissivity, which
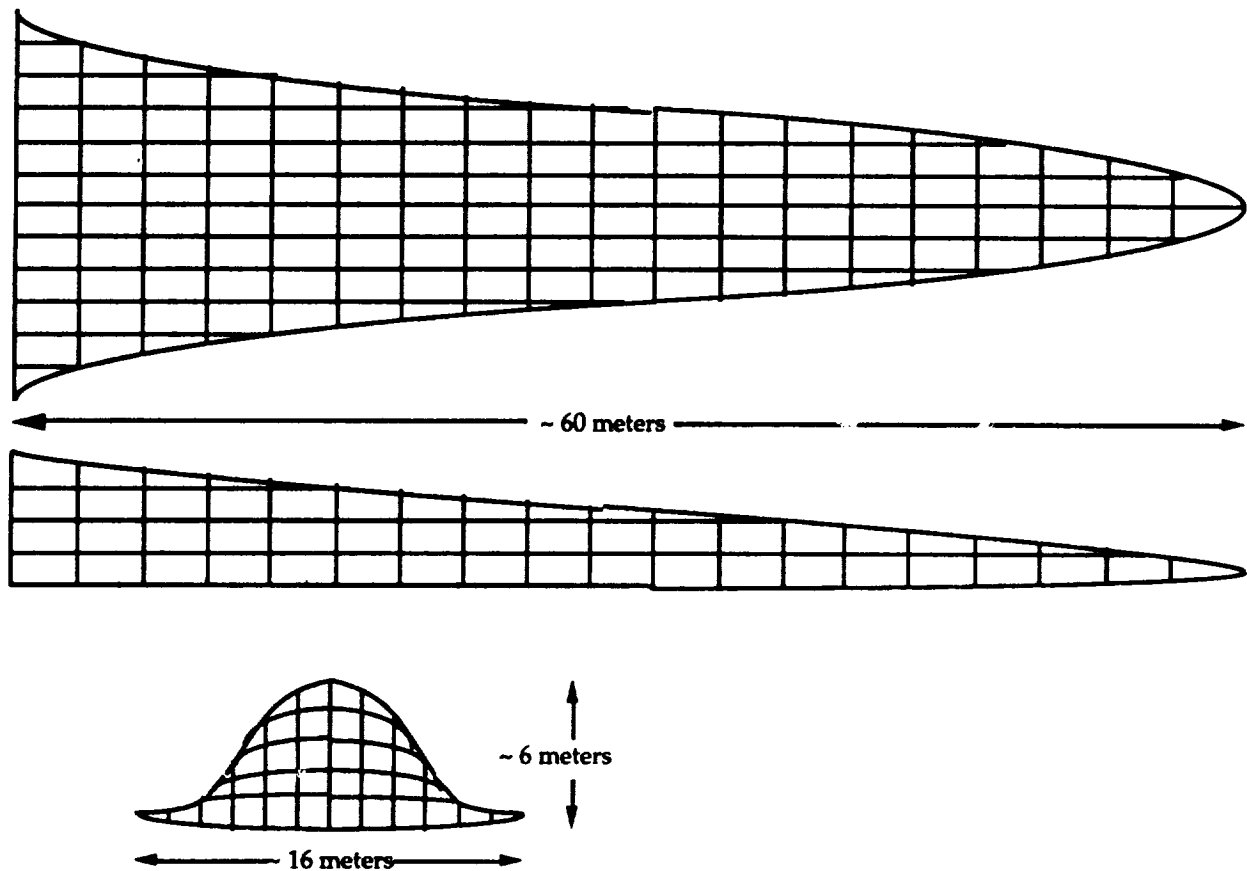
Fig. 1. Waverider Configuration

is a key in reducing surface temperature. ACC is extremely lightweight, with a density of about 1.7 g/cm³. To maintain aerodynamic integrity of the vehicle, ablation will not be used to control the temperature. Instead, a combination of chemistry effects, radiative energy, and conduction (active cooling) will be employed. An active, heat pipe design will be integrated into the leading edge. The heat pipes are extremely thin tubes of tungsten with the liquid metal, lithium, as the working fluid.

The waverider will have a double leading edge design (Fig. 2). The original leading edge will conform to the computer-generated waverider shape. This leading edge will comprise the the first 25 m of the waverider and will have its own heat pipe system. In essence, the waverider's first 25 m will simply be a shell to provide the proper waverider configuration. This original leading edge will perform the aeroassist maneuver at Venus and the aerobrake at Mars. While in LMO, this leading edge will be pyrotechnically separated from the remainder of the vehicle. The new vehicle will consist of the new leading edge, complete with its own heat pipe system and the life support module. Several reasons exist for using a double leading edge design. While performing two atmospheric maneuvers, the original leading edge could conceivably suffer some damage that would affect its aerodynamic capability. Thus the waverider will have a new
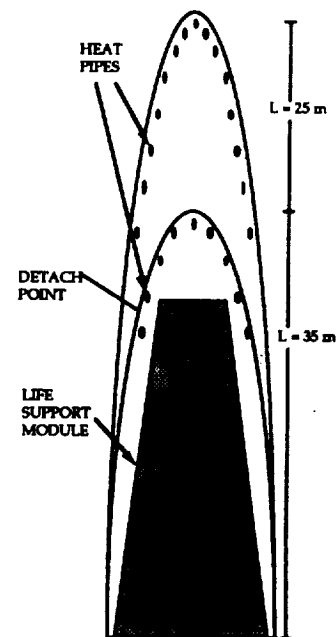

Fig. 2. Waverider Double Leading Edge with Heat Pipe Configuration

leading edge for its return trip to Earth, which is particularly important for aerobraking. In addition, the new leading edge will be more blunt than the original. This will not only reduce the maximum temperature and heating values, but will also increase drag, thus reducing the amount of time needed to slow down in Earth's atmosphere. Finally, by separating the original leading edge, the waverider mass will be greatly reduced. This will reduce the amount of fuel that must be transported by the cargo ship to Mars for the return trip to Earth.

With regard to the manned Mars mission project, a new approach must be considered: the aerogravity assist (AGA). Gravity-only assists rely simply on celestial mechanics, whereas an AGA also depends on aerodynamics. This maneuver incorporates a vehicle with high aerodynamic lift such that this lifting force augments gravity in balancing the centrifugal force on the vehicle by flying upside down. This equilibrium allows the vehicle to fly through the planetary atmosphere at a constant altitude. With a high lift-to-drag ratio, the amount of time in the atmosphere can be maximized as desired. This aspect of the maneuver is particularly applicable to the waverider configuration. Lift-to-drag ratios of 7-10 have been demonstrated and an L/D of 15 has even been exhibited for the Cytherean atmosphere. Such a maneuver can reduce the ΔV required or the time of flight to a given destination.

Since the shortest time to Mars was desired, the fastest trajectories possible were selected as candidates for the flight out. These were subjected to the constraints that a maximum ΔV of 9 km/sec is available for LEO departure and a maximum ΔV of 14 km/sec can be achieved with an aerobrake at Mars (the g-forces for higher speeds become intolerable). The time of flight (TOF) for the trip out is 108 days with a stay time of 0-220 days on the surface of Mars. The TOF for the return trip is 178 days.

The waverider will be propelled to Mars by a chemical engine using LOX and LH₂ as fuel and it will be propelled back to Earth by a solid-core, nuclear engine using LH₂ as fuel. The nuclear engine has an I_{sp} of 1150 sec and requires 89,101 kg of fuel to power a 50,000-kg waverider, while a chemical engine, with an I_{sp} of 450 sec requires 436,262 kg of fuel to power the same waverider. Because of volume restrictions, the waverider propulsion system has to be external to the ship (Fig. 3) and must be detached before entering the atmosphere of Venus. Even though the nuclear engine outperforms the chemical engine, the chemical engine was chosen for the flight to Mars because it would cost less to discard one, instead of two nuclear engines. The nuclear engine is the better choice for the return trip because it requires less fuel, an amount within the limits of the cargo ship payload capacity.

A major concern for any mission in space is providing enough food, water, and oxygen for the astronauts to survive the mission. To provide these life support supplies, an integrated regeneration system, also known as a closed loop system, is proposed. An integrated regeneration system is very complex. It involves carbon dioxide removal and concentration, carbon dioxide reduction, oxygen generation, water reclamation, solid waste removal and processing, nitrogen generation, and storage for all of these processes. Storage is
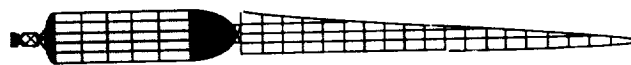

Fig. 3. Waverider with Chemical Booster

very important because the output of one subsystem is the input to another. Matching flow rates will be very difficult. Providing storage for each subsystem helps to eliminate this problem. The same type of regeneration systems used on the waverider will be used on the martian base. The power supply for these systems and all other systems on the waverider will be a 300 W/kg solar array.

During a manned Mars mission the astronauts will require shielding from Van Allen belt radiation, galactic cosmic rays, and solar cosmic rays (also known as solar flares). Shielding for radiation from the nuclear engine will be incorporated in the design of the engine. A bunker area will be incorporated into the waverider design to protect the astronauts during solar flares.

CARGO SHIP

The cargo ship, as its name implies, is an unmanned, interplanetary vehicle that carries supplies and equipment needed by astronauts on the surface of Mars (Fig. 4). It will be assembled at the Space Station with several components that will be constructed in the space environment near the Space Station. The waverider will leave low Earth orbit when the cargo ship successfully arrives at Mars where it will remain in LMO until rendezvous with the waverider. At this juncture, the astronauts will disassemble the components of the cargo ship needed on Mars and send them down to the surface.

The cargo ship is made up of several components including the nuclear reactor, radiation shield, heat radiator, argon fuel for magnetoplasmadynamic (MPD) thrusters, six ion attitude control thrusters, and seven MPD main thrusters. Payload includes the return hydrogen fuel and nuclear engine for the waverider, the NIMF shuttle, and two cargo capsules containing martian base supplies and surface life support.
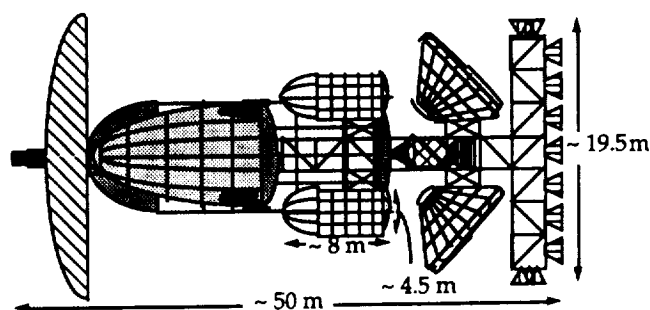

Fig. 4. Cargo Vehicle

The cargo ship is a vehicle connected by a truss to give flexibility in the arrangement and accessibility of each component. It is a desirable structure because of the loads that it sustains. Its main force of action is along its axis, which allows for a design to withstand optimal tensile and compressive stresses. Buckling loads on the members are more significant than tensile and compressive loads, thus the design is to disallow buckling (and axial stresses).

The materials considered for truss members are titanium and graphite epoxy. Titanium is used for nodes (connection elements) of the truss. In using the composite, graphite epoxy, for the individual truss members, strength increases while density decreases, therefore weight decreases. The members are also clad with aluminum to prevent erosion.

The cargo capsules that will be sent down to the surface of Mars will have the configuration of the Apollo capsules. This shape offers several desired characteristics. It has a high drag coefficient, which is required for the rapid deceleration in thin martian atmosphere. It decreases heating on the undersurface of the capsule because of the large radius of curvature, which increases the distance between the surface and the shock. Also, if designed correctly, the structure will be stable about one orientation only. This means that during initial reentry, no matter what the attitude of the vehicle is, it will stabilize about the nose forward orientation without an attitude control system.

Reentry will utilize two decelerators: parachutes and retrorockets. The parachutes will be stowed in a small compartment at the apex of the capsule. After deployment of the chutes, the landing gear will be extended and the heat shield for the retro rockets will be discarded exposing the nozzles, which will fire to decelerate to a soft landing velocity.

The materials considered for the capsules are carbon-carbon composites and aluminum alloys. The composites are used for the undersurface of the capsule, which experiences the greatest heat. It was calculated that 1400 K would be reached, which can be easily withstood by the composite material. The infrastructure of the capsules will probably be made out of materials such as boron-aluminum.

The purpose of the cargo ship is to deliver a maximum payload both efficiently and inexpensively to Mars. Since mission time is not of great importance, a low-thrust orbital maneuver can be considered for this cargo vehicle. A nuclear-electric propulsion system was compared to both advanced chemical boosters and a nuclear-thermal rocket as possible options for this mission.

A nuclear-electric propulsion (NEP) system was determined to be the most attractive propulsion option. It consists of a multimegawatt nuclear power plant that generates electricity necessary to operate the MPD thrusters. The MPD thrusters generate an electrical arc between an anode and a cathode that ionizes the propellant. The resulting plasma is then electromagnetically accelerated through the MPD nozzle to create thrust. The resulting exhaust velocity is extremely high, and specific impulse values ranging from 3000 to 9000 sec can be attained.

Since fuel mass is related exponentially and inversely to specific impulse, large fuel savings can be achieved by using an NEP system. In order to transport a 200,000-kg payload from LEO to martian parking orbit, only 134,000 kg of fuel would be required. This is significantly less than the fuel required for chemical (855,770 kg) and nuclear-thermal (235,406 kg) propulsion systems.

The spiral trajectory consists of three separate legs: Earth escape spiral, outbound coast, and martian capture spiral. The transfer begins with the 52-day Earth escape spiral during which the cargo vehicle slowly escapes the Earth's gravitational well by making many spiraling orbits. The spacecraft then coasts for several months until it refires its engines to straighten its orbit. When the cargo vehicle approaches Mars, it begins to spiral over a period of 39 days until it reaches martian parking orbit.

Since the spiral trajectory is a low-thrust maneuver, the total mission time is 601 days, or 1.65 years. This is significantly longer than a high-energy Hohmann transfer. A faster trip is not required, since the payload is only cargo; it is only necessary for the cargo ship to reach martian parking orbit before the waverider vehicle.

The main component of the nuclear-electric propulsion system is the nuclear power plant, which generates all the power necessary for the MPD thrusters and the onboard power systems. The nuclear reactor is a 5 MW$_e$/20 MW$_t$ distributed heat transport design. This type of reactor is favored over conventional solid-core reactors for safety reasons. The absence of a core pressure vessel increases the chances of core burn-up in case of an accidental atmospheric reentry. Also, in case of land impact, the core reactor will be in a subcritical configuration. The curved structure of the reflector prevents core compression in the case of impact.

The main engines for the cargo ship will be MPD thrusters. These engines ionize propellant and electromagnetically accelerate the resulting plasma to very high speeds. The plasma is then expanded out through a nozzle to produce thrust. Although MPD thrusters are presently still in the development stages, the prospect of using them in cargo-type, low-thrust missions is extremely attractive.

Exhaust velocities have been measured ranging from 15,000 to 80,000 m/sec in laboratory conditions. These can provide extremely high specific impulse values on the order of 1500 to 8000 sec. Thus the required fuel mass is significantly less than comparable chemical or nuclear-thermal systems. For this mission, seven MPD thrusters will be fired individually in succession. This will provide the necessary ΔV for a constant, low acceleration necessary to complete the spiral trajectory. A thrust of 115 N will be assumed for an I_{sp} of 4000 sec. The MPD thrusters will use argon as a propellant.

SURFACE MISSION

The major components of the surface mission are the NIMF shuttle, the 5-MW nuclear reactor power supply, the main dome, the two landing capsules, the life support and recycling equipment, the scientific payload, the rover, the extraction equipment, and miscellaneous piping, wiring, and tankages. The surface mission will last about three months. It will entail a large number of short-range, 2-5 km missions around the

main base and multiple long-range missions to several sites of interest. During these missions, experiments will be set up and samples will be collected at the various sites.

A geodesic dome was chosen for the martian base (Fig. 5). The most volume-efficient structure was sought so that interior living space could be maximized while minimizing total surface area. Therefore, the material mass required to be transported to the martian surface will be minimal. The sphere is the most volume-efficient shape and this can be conveniently represented by a geodesic dome. To achieve the volume necessary to house 10 astronauts, required life support, and miscellaneous equipment, a 5/8 dome of 7.62-m (25-ft) radius was selected (5/8 refers to a dome larger than a hemisphere). The dome will be partially buried and sandbags will be used to cover the upper portion in order to shield against radiation. Shell construction can be completed by 10 people in 1-3 days.

A vehicle using indigenous fuel as a propellant in a nuclear thermal engine is a NIMF (Fig. 6). The NIMF shuttle will have three primary functions. First, it will be used to transport the 10 astronauts from LMO to the martian surface. Second, the NIMF will be used for exploratory missions, traveling about the martian surface refueling itself with liquid CO_2. When the surface mission is over, the NIMF will transport the 10 astronauts back to LMO to rendezvous with the waverider.

COST ANALYSIS

The costing model for this mission was broken up into two parts: waverider and cargo mission. This model generates a bottom-line cost based on the mass of the two interplanetary vehicles. Personnel costs are derived from the bottom-line cost. Since the vehicles for this mission will be constructed and launched from the Space Station, cost estimates had to be calculated for Earth-to-Space-Station launches, construction at the Space Station, and fuel storage costs. All cost estimates are added to the bottom-line cost and the values are inflated to the year 2012 values.

The waverider is estimated to cost $92.56 billion and the cargo ship is estimated to cost $101.243 billion. Total cost of the mission is estimated at $193.803 billion for the year 2012.
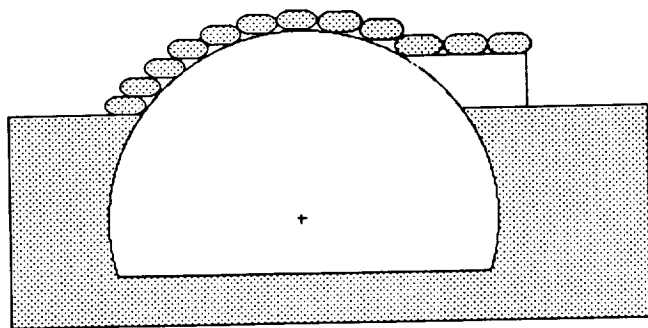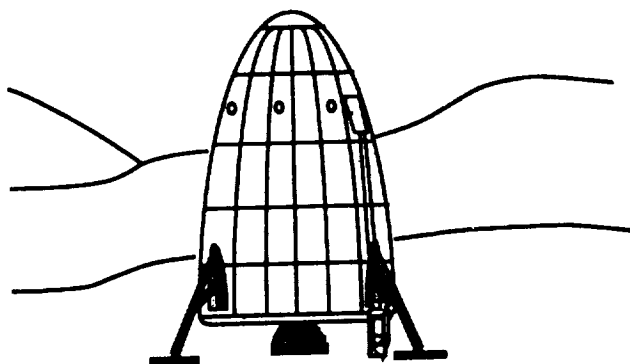

Fig. 5. Geodesic Dome for the Martian Base

Fig. 6. NIMF Lander

CONCLUSION

The Request For Proposal called for the use of a hypersonic waverider to transport 10 astronauts to Mars for a 3 to 5 month exploratory mission by the year 2025. It also called for using the waverider for an aerogravity assist through the atmosphere of Venus. Other criteria for the Request For Proposal were minimum time of flight, minimum cost, minimum launch mass from Earth, maximum payload delivery to Mars, safe human environment, and practicality of accomplishment with projected technology in the desired timeframe.

The waverider will be constructed entirely of advanced carbon-carbon (ACC), which is lightweight but very durable. The waverider will experience extreme temperatures in the atmospheres of Venus, Mars, and Earth because of very high relative velocities. ACC was chosen as the best material to handle all loads encountered and keep the vehicle mass at a minimum. By performing the aerogravity assist through the atmosphere of Venus, the waverider achieves a deflection angle and ΔV increase for the trip to Mars, as well as a launch window for a return trip, which is open for 7.5 months. The Venus gravity assist also allows for sequential launches of the cargo ship and waverider that will not require the cargo ship to stay in orbit for a couple of years before the waverider can dock with it. The waverider will be constructed with a double leading edge so that the outer portion can be removed after the Mars aerobrake maneuver. Removal of the outer leading edge reduces the vehicle mass and therefore reduces the return trip fuel mass requirements. The return propulsion system will be a nuclear solid core engine that uses H_2 as a propellant. The engine performance characteristics far outweigh those of a chemical engine and the fuel mass requirements are considerably less. The aerobrake maneuvers at Mars and Earth eliminate the need for a propulsion system for deceleration. Life support aboard the waverider will incorporate an integrated regeneration system instead of all stored supplies. Life support also includes the design of an artificial gravity centrifuge to help counteract the effects of microgravity.

The cargo ship, which is a long truss with all the payload attached to it, travels to Mars on a spiral trajectory using a nuclear electric propulsion system. The NEP system consists

of a nuclear electric power plant, MPD thrusters, and ion attitude control engines. The MPD thrusters and ion engines both use argon for a propellant. The NEP system requires a longer mission time than any of the other propulsion systems considered; however, it also requires the least fuel mass. The nuclear electric engine that powers the cargo ship has an operating lifetime of seven years. This engine will also be the power plant for the Mars base.

The Mars base will be constructed mostly underground to shield from solar radiation. It is also constructed from ACC. The base is a 5/8 dome that can be constructed in 1-3 days. It will provide a shirtsleeve environment for the astronauts as well as a permanent structure for future missions. The NIMF shuttle, which is propelled by essentially the same engine used to return the waverider to Earth, will be used to transport the astronauts to and from LMO as well as around the planet. The shuttle uses CO_2 as a propellant, which will be extracted from the martian atmosphere and compressed into liquid form. The NIMF shuttle makes it possible to study a wide range of locations on the planet, allowing extensive search for useful extractable materials that could lead to possible colonization of Mars.

The effort to reduce cost began by keeping mass at a minimum. With production scheduled to begin by the year 2012, financing a mission of this size will have to be done on an international scale. Much of the new technology such as the waverider, nuclear solid-core engine, MPD thrusters and total regenerative life support systems will require more research. Pushing technology is the key to reaching the point that the first stone can be laid for a mission like this. Without a tremendous push for more research and development, man may never set foot on Mars.